NSG-179-61

UNPUBLISHED PRELIMINARY DATA

18p.

N64-26805

Code-1 Cat. 15

NASA CR-58055

Silicon Photodiode Vacuum Ultraviolet Detector*

A. J. Tuzzolino

Laboratories for Applied Sciences, The University of Chicago, Chicago 37, Illinois

26805

ABSTRACT:

The photosensitivity of silicon surface-barrier photodiodes has been measured over the photon energy range from 4.9 to 21.2 ev (2537 to 584Å). The photodiodes are operated in the reverse-bias mode at room temperature. The sensitivity of a typical photodiode with approximately 100Å of gold on the sensitive surface is 0.16 electrons/photon at 2536Å and 1.1 electrons/photon at 584Å. The photosensitivity is uniform over the sensitive area (0.56 to 2.75 cm^2) to within a few percent. The operating characteristics of these devices are reported and the use of the silicon photodiode directly, or in combination with sodium salicylate, as a vacuum ultraviolet detector is discussed.

AUTHOR:

OTS PRICE

XEROX $ 1.60ph

MICROFILM $ ______

REPORTS CONTROL No. ______

1. INTRODUCTION

Of growing importance in both the laboratory and in the space sciences is the need for detectors which are sensitive to ultraviolet radiation. This need has led, in recent years, to a variety of ultraviolet photodetectors. Excellent discussions of the use of thermocouples, phosphor-coated photomultiplier tubes, and of recently developed ultraviolet photodetectors of the photoemissive, ion chamber, and other types may be found in the literature.[1-5]

The operating characteristics of various types of photodiodes in the visible and near-ultraviolet regions of the spectrum have been studied for some time,[6-14] but very little information is available on photodiodes suitable for use as detectors in the vacuum-ultraviolet. This paper describes the operating characteristics of the silicon surface-barrier photodiode over the photon energy range from 4.9 to 21.2ev (2537 - 584Å) and the use of this photodiode directly, or in combination with sodium salicylate, as a vacuum-ultraviolet detector. The work reported here represents an extension of earlier experiments,[11] where the photoresponse of the silicon surface-barrier photodiode was studied in the visible and near-ultraviolet (5461 - 2537Å).

2. PHOTODIODE

A silicon surface-barrier photodiode as used in this experiment is shown schematically in Fig. 1. The space-charge region extends from $x = 0$ to $x = W(V_o)$, where V_o is the applied bias voltage. The nature of the space-charge region and the operating characteristics of this type of photodiode in the visible and near ultraviolet are discussed elsewhere.[15,11] The high electric field which exists in the space-charge region of such a reverse-biased photodiode will separate any electron-hole pairs generated in the high field region by a photon, resulting in a photocurrent in an external circuit. We consider first, the case where the vacuum-ultraviolet radiation is incident on the photodiode directly and in Sec. 5, the case where the radiation is incident on a sodium salicylate film located in front of the photodiode.

Referring to Fig. 1, let F be the steady state flux density of photons of wavelength λ transmitted by the gold film at $x = 0$. Then, the number of electron-hole pairs produced per unit time per cm^3, $g(x)$, at any x is

$$g(x) = \eta F \alpha e^{-\alpha x} , \tag{1}$$

in which η is the quantum efficiency of silicon, defined as the number of electron-hole pairs produced as a result of the absorption of one photon of wavelength λ, and α is the absorption coefficient for the photons, which are assumed to be monochromatic. It can be shown[8, 11] that as a result of this volume generation rate, the photocurrent in the photodiode is

$$I_{ph} = -q\eta T' N_o (e^{-\alpha W} - 1), \tag{2}$$

in which q is the electronic charge, T' is the transmittance of the gold film and is defined[11] as the ratio of F to F_o, N_o is the number of photons per unit time incident on the gold film, and W is the depth of the barrier region. Since the optical absorption coefficient of silicon is very large ($> 10^5$ cm^{-1}) in the wavelength interval considered here

$(2537 - 584\text{Å})$[16], and $W \approx 50\mu$ under operating conditions,[11] the exponential term is negligible, and Eq. (2) reduces to

$$I_{ph} = q\eta T' N_o. \quad (3)$$

The sensitivity S of the photodiode is defined here as

$$S(\text{electrons/photon}) = I_{ph}/(qN_o). \quad (4)$$

The quantity S is the number of electrons flowing in an external load resistor (Fig. 1) per photon incident on the photodiode.

The photodiodes were operated in the reverse-bias mode, so that the total current in the diode is the sum of the "dark" current and the photocurrent given by Eq. (3).[11] Under experimental conditions, the diodes were operated at 6 volts reverse bias, in which case the dark currents ranged from $\approx 1 \times 10^{-8}$ to $\approx 1 \times 10^{-7}$ amp. The photocurrents were in the range $\approx 3 \times 10^{-10}$ to $\approx 5 \times 10^{-12}$ amp, making dc measurements of the photocurrents difficult in the presence of such large dark currents. To eliminate this difficulty, the light incident on the photodiodes was chopped at 13 cps and the ac signal across a load resistor was amplified, rectified, and measured with a voltmeter.

The low frequency equivalent circuit of a photodiode and preamplifier is shown in Fig. 2, where quantities not affecting the performance of the photodiodes as used here are omitted.[11] The current generator I_{ph} accounts for the ac photocurrent, R_B is the back-resistance of the reverse-biased photodiode, R_L is the load resistance, and R_A is the input-resistance of the preamplifier. For the output signal to be proportional to the product $I_{ph} R_L$, R_L must be small compared to R_B and R_A. Under experimental conditions (reverse bias of 6 volts), the output signal was proportional to the product $I_{ph} R_L$ for all ranges of photocurrents and load resistance values used. An important advantage in operating the photodiodes in the reverse-bias mode is that a very large range of linearity of photodiode signal with photon flux is possible.[14] The output signal was also measured as a function of applied bias (1 to 22.5 volts) and was found to be independent of the applied bias. The procedures employed to calibrate the electronic apparatus used in this work are described elsewhere.[17]

3. EXPERIMENTAL METHODS AND RESULTS

The general techniques used in the fabrication of the photodiodes were similar to those described in detail elsewhere.[18] Single-crystal n-type silicon was used as the starting material. The electrical resistivity ranged from 700 to 4000 ohm-cm and the minority carrier lifetime ranged from 400 to 2000μ sec.[**/] The sensitive areas of the finished photodiodes ranged from 0.56 to 2.75 cm^2. The optical system which was used is described in detail in earlier work,[17] and consisted of a Jarrell-Ash, one-meter, vacuum monochromator and a discharge lamp similar to the lamp described by Hartman.[19] Hydrogen, helium and neon were used in the lamp.

A sample chamber[17] was mounted to the exit slit chamber of the monochromator and contained the photodiode sample and a calibrated photon detector. The pressure in the sample chamber was held below 1×10^{-3} mm Hg. The calibrated photon detector consisted of a RCA-6199 head-on-type photomultiplier tube with a coating of sodium salicylate on the end of the glass envelope. This system was calibrated by means of a calibrated nitric oxide chamber.[5]

The spectral sensitivity of a typical photodiode with an area of 2.75 cm^2 and a nominal gold thickness of 100Å is shown in Fig. 3. The uncertainty in the value of S, estimated from repeated measurements on this photodiode, is indicated by the vertical lines. The sensitivity is seen to increase slowly with increasing photon energy from 4.9 to $\approx$ 10 ev and for $h\nu > 10$ ev, S increases rapidly with increasing photon energy. Measurements of the type shown in Fig. 3 were carried out on five photodiode samples, each having a gold film thickness of approximately 100Å. In all cases, the wavelength dependence of the measured sensitivities was identical to that shown in Fig. 3, the only difference being in the absolute magnitude of the sensitivities. The magnitude of S at a given wavelength depends critically upon the thickness of the gold film on the sensitive surface, since the transmittance T' in Eq. (3) depends upon the film thickness. The dependence of T' on gold thickness is particularly strong at the shorter wavelengths ($h\nu > 10$ ev) because of the strong absorption by the gold film.[20] When care was taken to evaporate the gold film uniformly over the sensitive surface, the local response[11] over the sensitive surface of a photodiode (2.75 cm^2) was found to be uniform to within a few percent.

4. DISCUSSION

If the transmittance T' were known, it would be possible to calculate S from Eq. (3) since the quantum efficiency η has been measured over the photon energy range considered here.[17] In general, any calculation of the quantity T', which is equivalent to calculating the transmittance of a single absorbing layer (Au) on an absorbing substrate (Si), will be unreliable since the effective optical constants of metallic films with thickness of the order of 100Å depend strongly upon the film thickness and manner of film deposition.[21] In addition, the effects of any oxide film between the silicon surface and the gold film would have to be considered.[17] For these reasons, no attempt was made to calculate the transmittance.

The strong increase in S for $h\nu > 10$ ev may be understood by considering the wavelength dependence of η, which is shown in Fig. 4.[17] One sees that η increases very rapidly for $h\nu > 10$ev, and since S equals the product of T' and η, the strong increase in S above $h\nu = 10$ ev is attributed to the strong increase in η. The fact that S does not increase as strongly as η with increasing $h\nu$ above 10 ev results from the factor T', which decreases at the shortest wavelengths with increasing $h\nu$.[20]

5. SODIUM SALICYLATE PHOTODIODE COMBINATION

The possibility of using a silicon photodiode in combination with a scintillator crystal for the detection of charged particles has been demonstrated,[11] and a sodium salicylate-silicon photodiode combination has been used to measure photon intensities in the vacuum ultraviolet.[17,22] In both applications, the photodiode was used to detect the visible light emitted by the scintillator crystal or the sodium salicylate.

In the case of the sodium salicylate-photodiode (SSP) combination, a photodiode is mounted directly behind a glass window onto which a layer of sodium salicylate has been sprayed. The radiation is incident on the sodium salicylate film and a fixed fraction of the visible light emitted by the salicylate film is measured by the photodiode. The photocurrent, I_{SSP}, in the photodiode is

$$I_{SSP} = c\ N(\lambda) \quad , \tag{5}$$

in which $N(\lambda)$ is the photon flux incident on the sodium salicylate, and the quantity c depends upon the quantum efficiency of silicon, the quantum efficiency of the sodium salicylate film, the transmittance of the gold film, and the angular distribution of the visible radiation emitted by the sodium salicylate. For a given SSP combination, c is a constant independent of wavelength. The constant c was evaluated for a SSP combination by measuring the photocurrent in the photodiode[17] resulting from a known photon flux (1216Å) incident on the salicylate. The photon flux at 1216Å was determined by means of a calibrated nitric oxide chamber.[5] Substitution of the determined value of c into Eq. (5) gives for this particular SSP combination

$$N(\lambda) = 1.1 \times 10^{20} I_{SSP} \quad , \qquad (6)$$

where the photocurrent is measured in amperes. For given photon fluxes, Eq. (6) serves to indicate the order of magnitude of the photocurrents to be expected for any SSP combination using a photodiode with ≈ 100Å of gold on its surface.

6. APPLICATIONS

The silicon photodiode used alone or in combination with sodium salicylate is a convenient detector for vacuum-ultraviolet radiation in any application where size, weight, and power consumption are problems. For ultraviolet intensities available from typical light sources used in the laboratory,[17] the performance of the silicon photodiode has been found to compare favorably with a thermocouple, phosphor coated photomultiplier tube, or gas ion chamber. The photodiodes may be operated at any convenient low reverse bias (≈1 volt) and have been found to be stable under vacuum. The sensitivity of a photodiode was found to be unchanged after the photodiode had been on a shelf for several months and the photodiodes will operate satisfactorily at elevated temperatures (≈50°C).

To illustrate the detecting limits of these devices, we consider the minimum photon flux which may be detected by a SSP combination or by a photodiode directly by considering the case where the ac photosignal across the load resistor R_L is applied to the input of a preamplifier characterized by an equivalent noise resistor R_N,[23] an input-resistance R_A, and an input capacitance C_A. The smallest radiation signal which is detectable will be determined by the noise generated by the detector circuit and associated preamplifier. Disregarding any "1/f" noise contribution from the photodiode,[24] the signal to noise ratio, s/n, per unit bandwidth at the input of the preamplifier is[23,25]

$$s/n = I_o/[\,2qI + 4kTG + 4k\,TR_N(G^2 + \underline{\omega}^2C^2)\,]^{1/2} \quad , \qquad (7)$$

where I_o is the rms photocurrent, I is the total current in the photodiode, G is the sum $1/R_B + 1/R_L + 1/R_A$, and C is the sum of the photodiode capacitance[11] and C_A. For small I, the thermal noise term predominates over the shot noise term. We assume R_L is much smaller than R_B and R_A and much greater than R_N and that terms involving $\underline{\omega}C$ may be neglected.[11] Setting the resulting expression equal to unity, the minimum detectable rms photocurrent I'_o is

$$I'_o = (4kT/R_L)^{1/2} \quad . \qquad (8)$$

From Eq. 8, one sees that I'_o may be decreased by increasing R_L. An upper limit for R_L is set by the condition that R_L be small compared to R_B and R_A.[17] Choosing R_L = 1 meg, Eq. (8) gives

$$I'_o = 1.3 \times 10^{-13} \text{ amp.} \qquad (9)$$

From Eqs. (9) and (4), the minimum detectable rms photon flux for a photodiode used as a detector directly is

$$N'(\underline{\lambda}) = I'_o/qS(\underline{\lambda}) = 8 \times 10^5/S(\underline{\lambda}). \tag{10}$$

For a photodiode having the sensitivity given in Fig. 3, $N' = 2.5 \times 10^6$ photons/sec at 1216Å. For the SSP combination with the calibration given by Eq. (6),

$$N'(\lambda) = 1.4 \times 10^7 \text{ photons/sec}. \tag{11}$$

It should be noted that for the SSP combination, the minimum detectable rms flux is independent of λ (Eq. (11)), whereas for the photodiode detector, it decreases with decreasing $\underline{\lambda}$ (Eq. (10) and Fig. 3). An advantage in using the SSP combination is that this combination detector need be calibrated at one wavelength only, whereas the photodiode detector must be calibrated at all wavelengths of interest. However, the minimum detectable photon flux is lower for the photodiode detector.

Although the above calculations are approximate, they serve to illustrate the order of magnitude of the detecting ability of the SSP combination or photodiode detector. The minimum detectable fluxes predicted by Eqs. (10) and (11) represent lower limits because of the approximations used in the calculations and the assumption of unit bandwidth. The minimum detectable fluxes for the SSP combination and photodiode detector used in the experiment described here were about a factor of ten greater than the values given by Eqs. (10) and (11).[17]

The silicon photodiode is particularly suitable for applications requiring "fast" ultraviolet detectors since studies of the high frequency capabilities of these devices indicate that a high-frequency cutoff in the megacycle range should be easily attainable.[11] In addition, the photodiodes may be conveniently fabricated in a variety of sizes and shapes to conform to different detecting geometries.

7. ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. J. Kristoff and Mr. C. Vossler for their help with the apparatus and assistance in making measurements, to Dr. J. Burns, Mr. J. Lamport, and Dr. J. Simpson for their continued encouragement and helpful criticisms, and to Mrs. R. Allison for preparing the sodium salicylate films.

FIGURE CAPTIONS

Figure 1. Silicon surface-barrier photodiode (not to scale).

Figure 2. Low-frequency equivalent circuit of a reverse-biased photodiode and preamplifier. Quantities not affecting the low-frequency operation are not shown. I_{ph} is a current generator accounting for the ac photo-current, R_L is the load resistance, R_B is the back-resistance of the photodiode, and R_A is the input-resistance of the preamplifier.

Figure 3. Spectral sensitivity for a typical silicon photodiode with an area of 2.75 cm^2 and a nominal gold film thickness of 100Å.

Figure 4. Quantum efficiency of silicon.

REFERENCES

*/ The research reported in this paper was supported by the National Aeronautics and Space Administration under NASA Grant NSG-179-61.

**/ The silicon used was obtained from Dow Corning Corporation, Hemlock Michigan, and Merck and Company, Incorporated, Danville, Pennsylvania. The resistivity and lifetime values were specified by the suppliers.

[1] D. M. Packer and C. Lock, J. Opt. Soc. Am. 41, 699 (1951).

[2] F. S. Johnson, K. Watanabe, and R. Tousey, J. Opt. Soc. Am. 41, 702 (1951).

[3] K. Watanabe and E. C. Y. Inn, J. Opt. Soc. Am. 43, 32 (1953)

[4] Appl. Optics 1 , (Nov. 1962).

[5] L. Dunkelman, J. Quant. Spec. and Rad. Trans. p. 533(Oct-Dec 1962).

[6] B. J. Rothlein and A. B. Fowler, IRE Trans. on Electron Devices ED-1, 67 (1954).

[7] D. E. Sawyer and R. H. Rediker, Proc. IRE 46, 1122 (1958).

[8] W. W. Gärtner, Phys. Rev. 116, 84 (1959).

[9] A. J. Jordcend and A. J. Milnes, IRE Trans. on Electron Devices ED-7 , 242 (1960).

[10] G. Lucovsky and P. H. Cholet, J. Opt. Soc. Am. 50, 979 (1960).

[11] A. J. Tuzzolino, E. L. Hubbard, M. A. Perkins, and C. Y. Fan, J. Appl. Phys. 33, 148 (1962).

[12] E. Ahlstrom and W. W. Gärtner, J. Appl. Phys. 33, 2602 (1962).

[13] R. P. Reisz, Rev. Sci. Instr. 33, 994 (1962).

[14] R. L. Williams, J. Opt. Soc. Am. 52, 1237(1962).

[15] W. L. Brown, Natl. Acad. Sci. Rept. NAS-NSS 32, Publ. 871, 9(1961).

[16] T. Sasaki and K. Ishiguro, Japan J. Appl. Phys. 2, 289(1963).

[17] A. J. Tuzzolino, Phys. Rev. 134, A205(1964).

[18] F. R. Shea, editor, IRE Trans. on Nuclear Sciences NS-8, (1961).

[19] P. L. Hartman, J. Opt. Soc. Am. 51, 113 (1961).

[20] T. T. Cole and F. Oppenheimer, Appl. Optics 1, 709 (Nov. 1962).

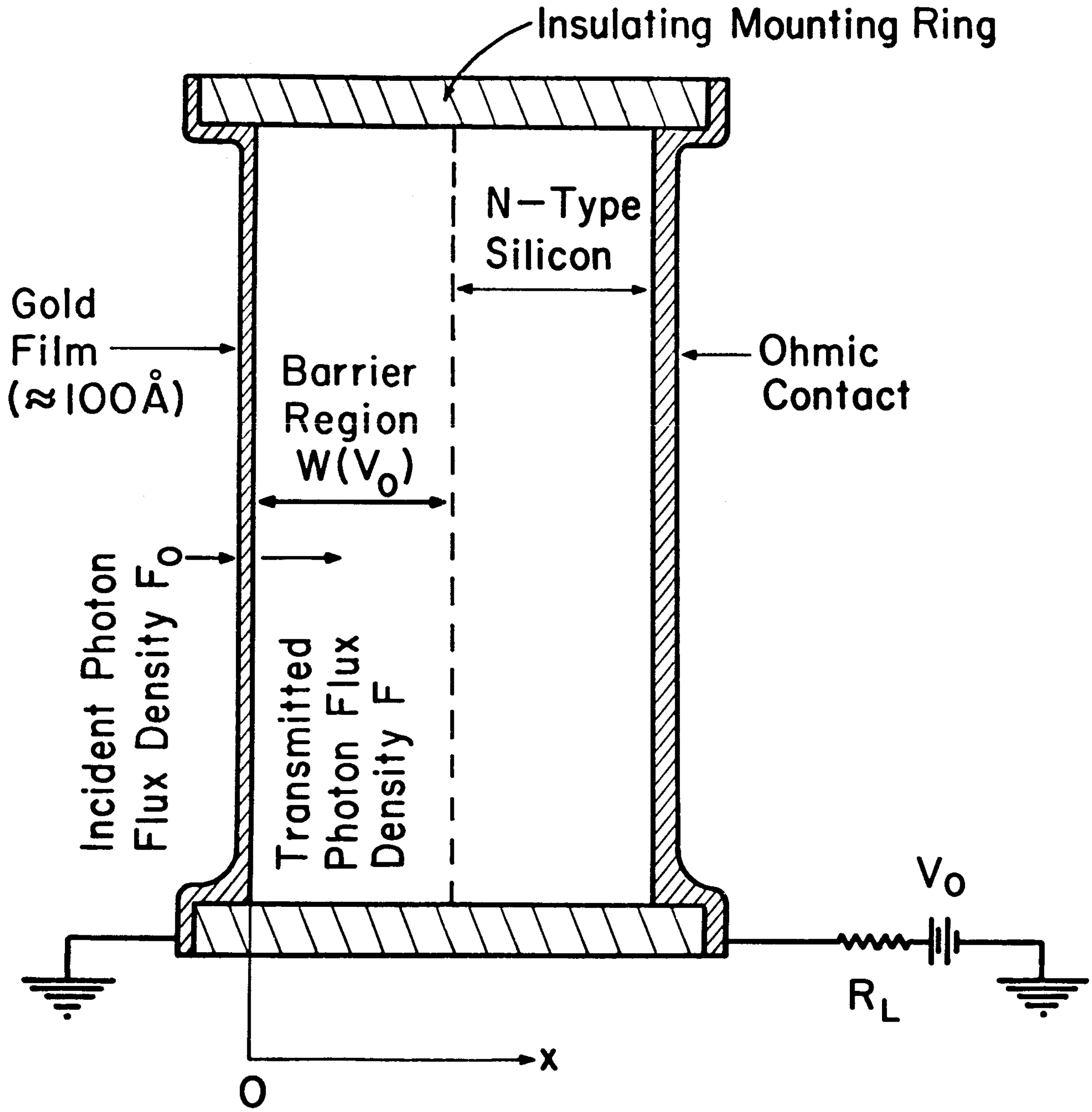
[21] O. S. Heavens, Optical Properties of Thin Solid Films (Butterworths Scientific Publications, Ltd., London, England, 1955).

[22] R. Allison, J. Burns, and A. J. Tuzzolino, J. Opt. Soc. Am. 54, 747 (1964).

[23] A. Van der Ziel, Noise (Prentice Hall, Inc. Englewood Cliffs, New Jersey, 1954), p. 97.

[24] A. Van der Ziel, Proc. IRE 43, 1639 (1955).

[25] A. Van der Ziel, Proc. IRE 46, 1019 (1958).



Insulating Mounting Ring
N-Type
Silicon
Gold
Film
(≈100Å)
Ohmic
Contact
Barrier
Region
W(V0)
Incident Photon
Flux Density F0
Transmitted
Photon Flux
Density F
V0
RL
x
0

Fig. 1

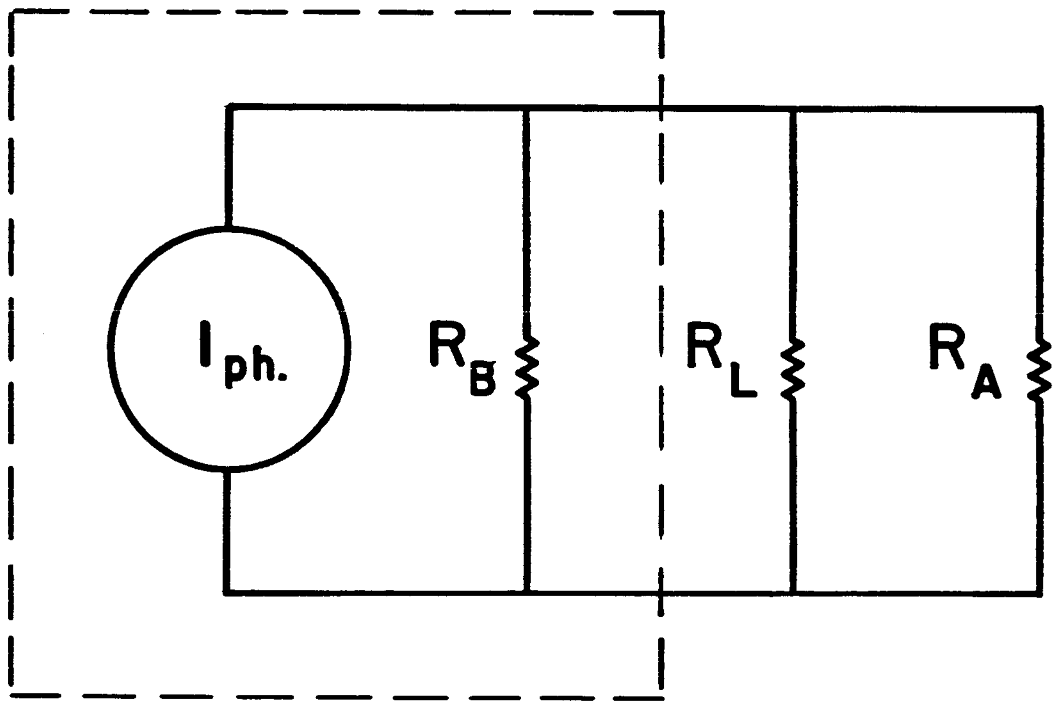


Fig. 2

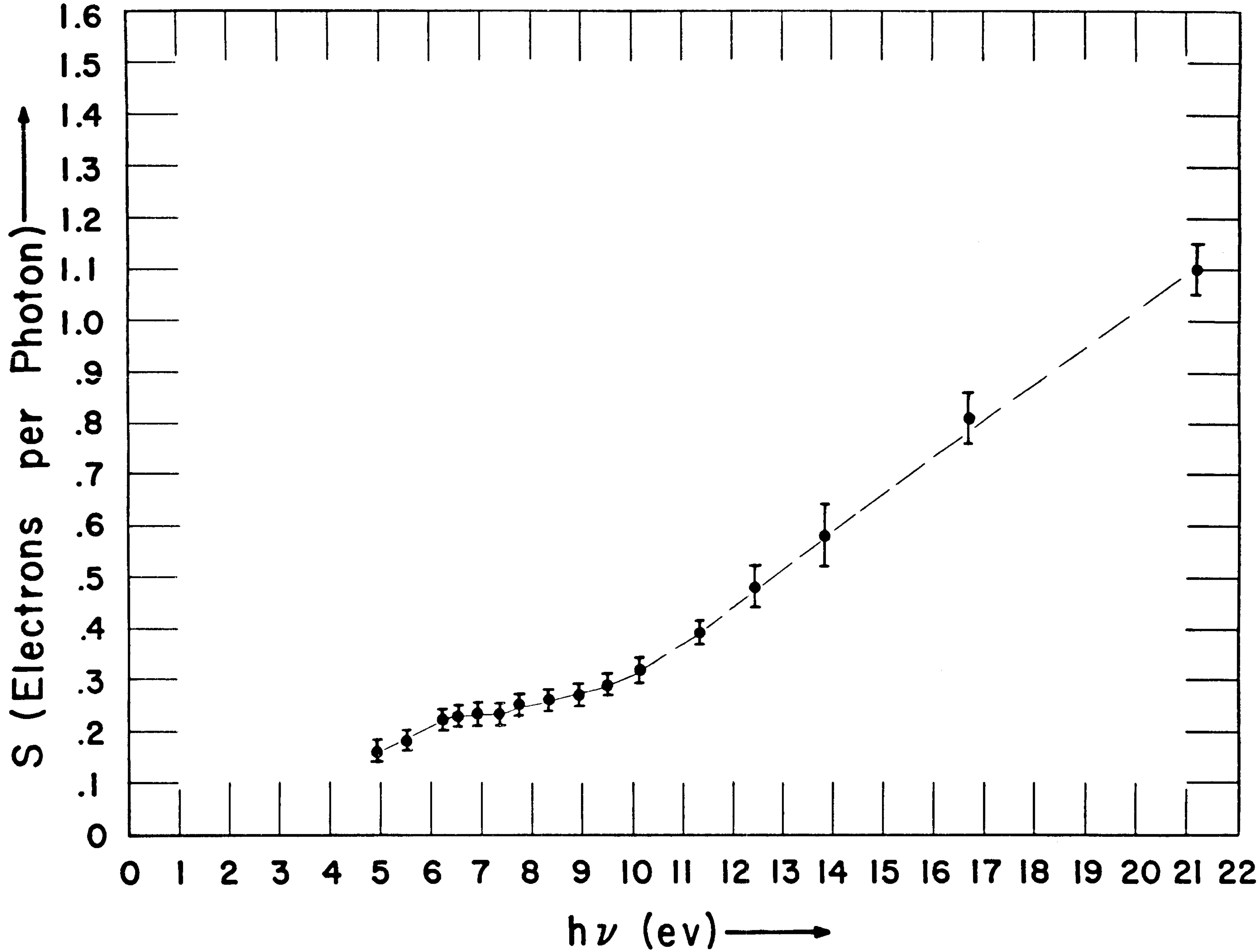
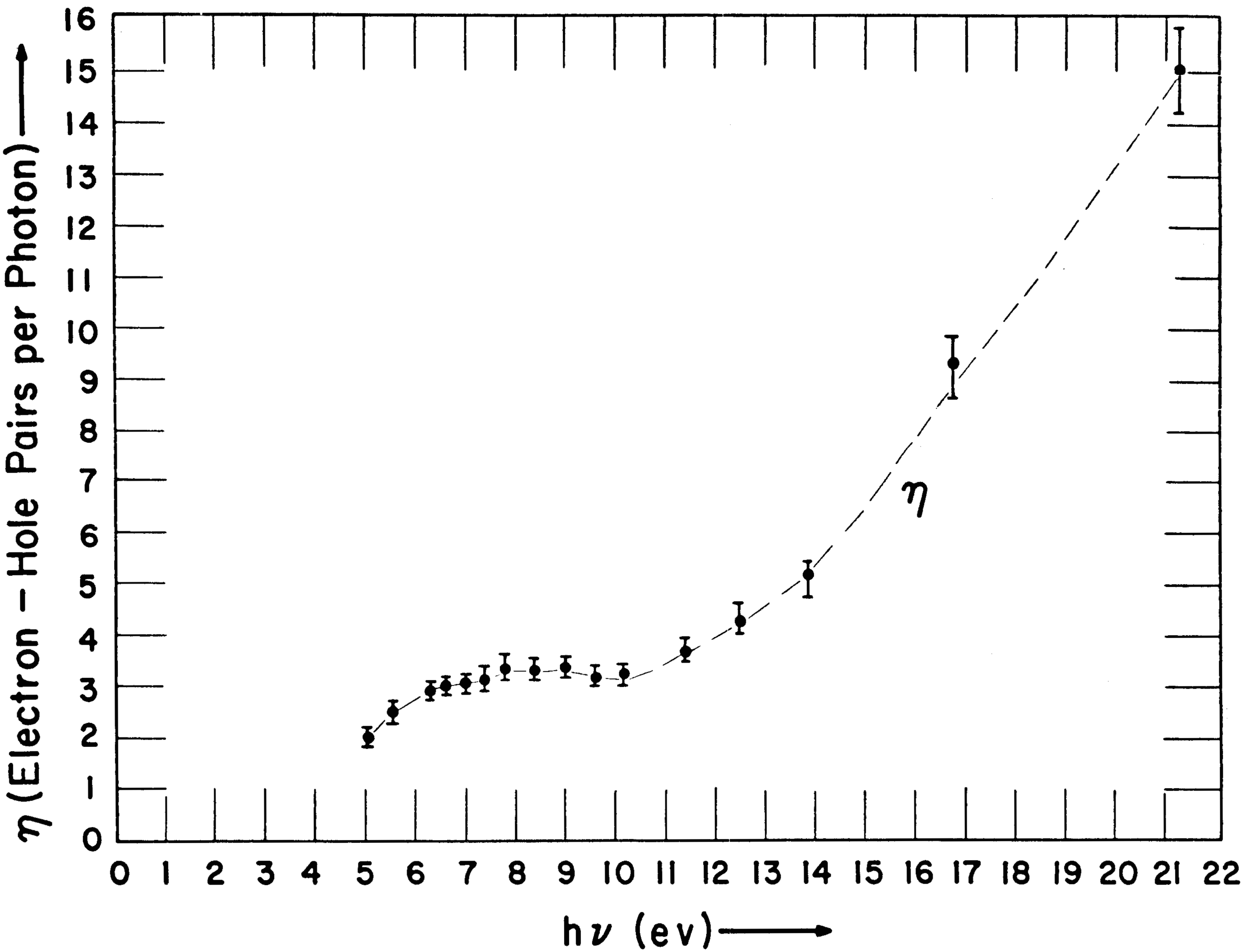

S (Electrons per Photon)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
hν (ev)

Fig. 3



η (Electron - Hole Pairs per Photon)
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
η
hν (ev)

Fig. 4